Finite temperature field theory and heavy ion collisions

Nordic Winter School on Particle Physics and Cosmology 2013, Skeikampen, Norway

Lecture 1: Heavy ion collisions; hydrodynamics

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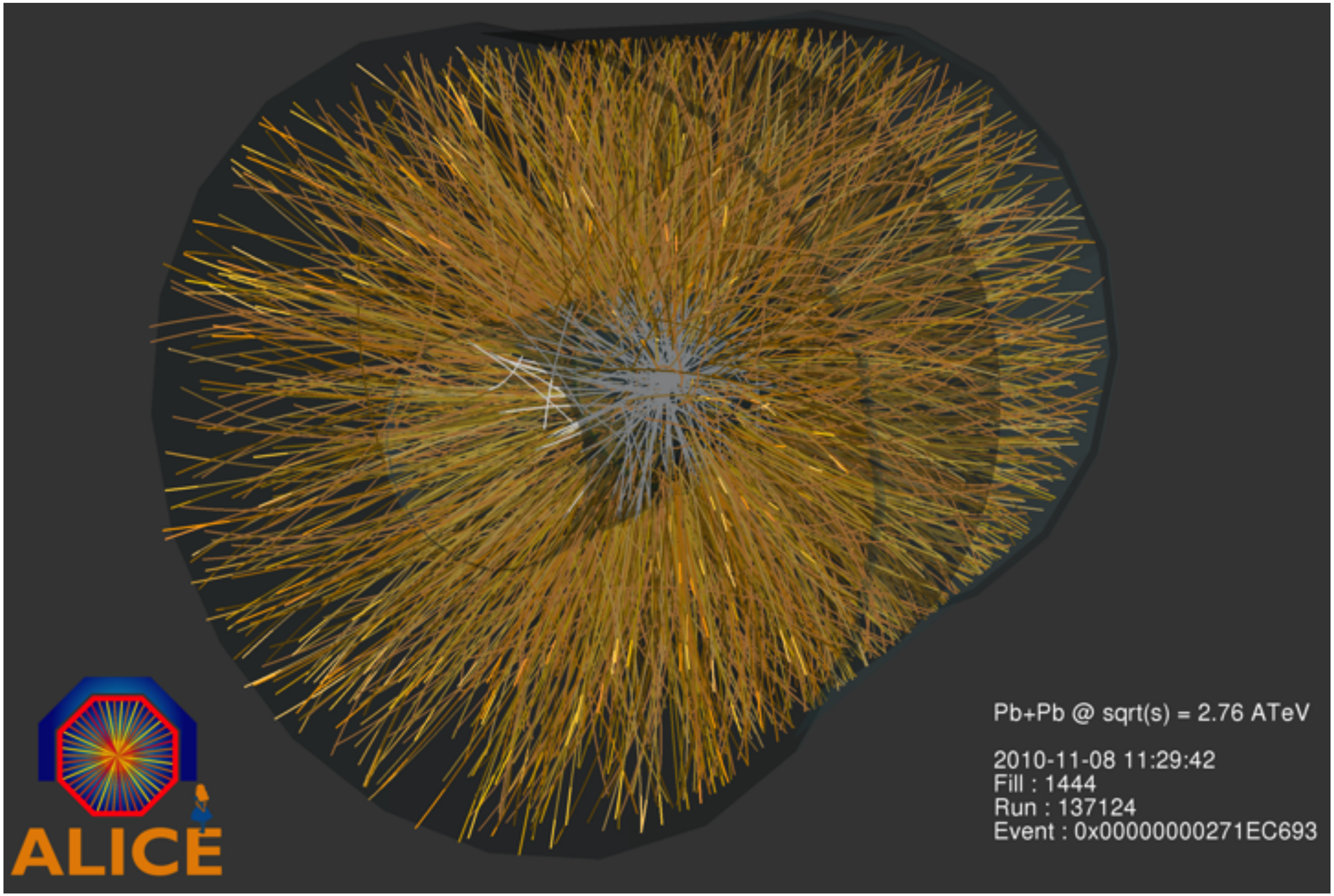
Plan for lectures

- Heavy ion collisions: main results, hydrodynamics description
- Finite temperature field theory (Schwinger-Keldysh)
- Spectral functions, properties and scales of weakly coupled plasmas
- Energy loss in a plasma and hard probes

- I'll be talking about something *relatively* cold

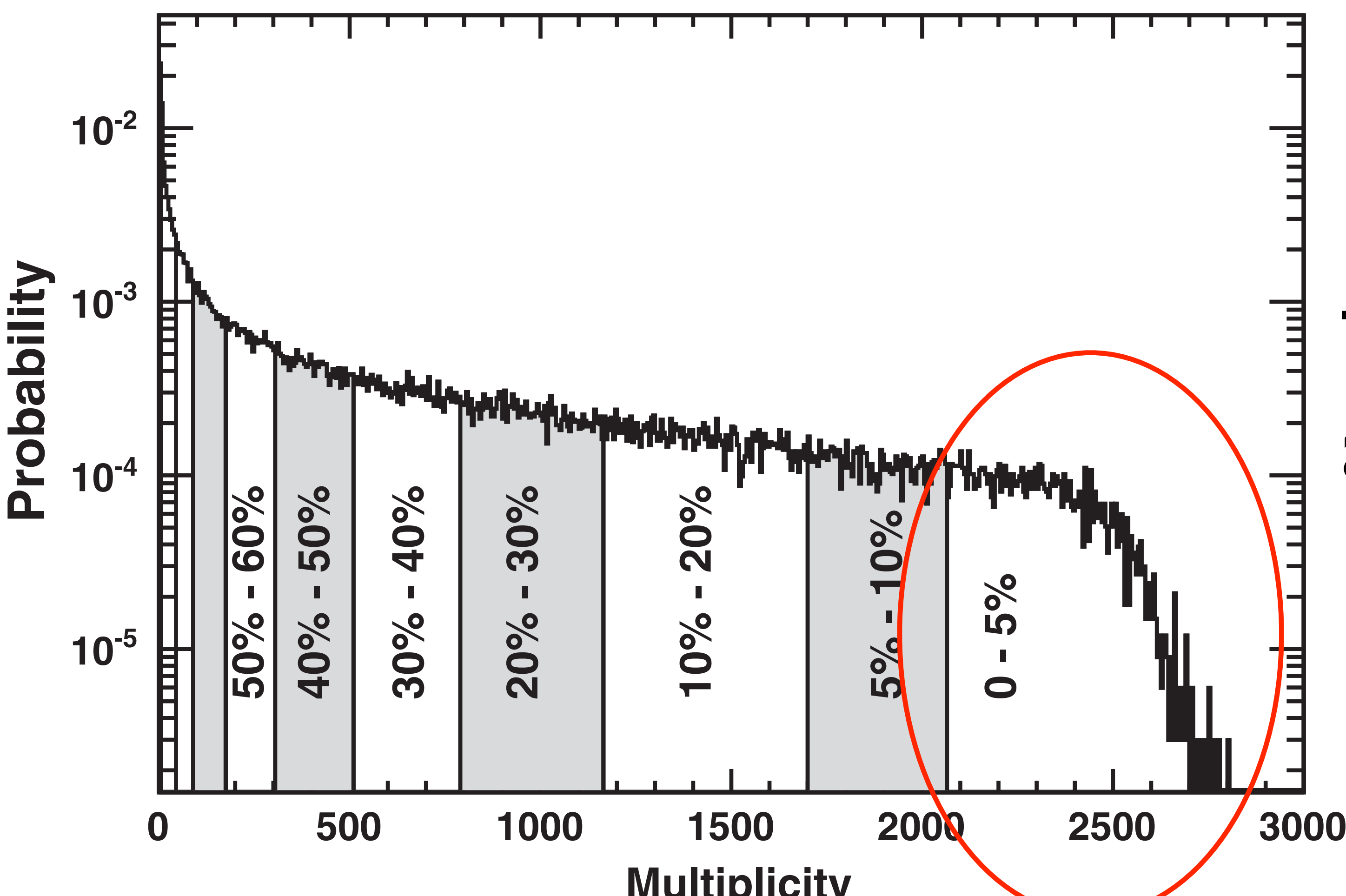


T~400÷500MeV (LHC) (~5 trillions K)

(*ultrarelativistic*) Heavy ion collisions

- Modern history:
  -RHIC (Brookhaven), Au+Au @$\sqrt{s_{NN}}$=200 GeV
  -LHC, Pb+Pb @ $\sqrt{s_{NN}}$=2.76 TeV
- Main goal is to study QCD, the theory of the strong interactions, around and above the *deconfinement transition*
- First energies at which there is evidence for a new *deconfined* phase of matter

- Integrated luminosity ~160 μb^{-1} (Atlas&CMS 2011, Alice is a bit lower)
- Total Pb-Pb cross-section σ~7÷8 b
- Multiplicity is extremely well correlated with impact parameter



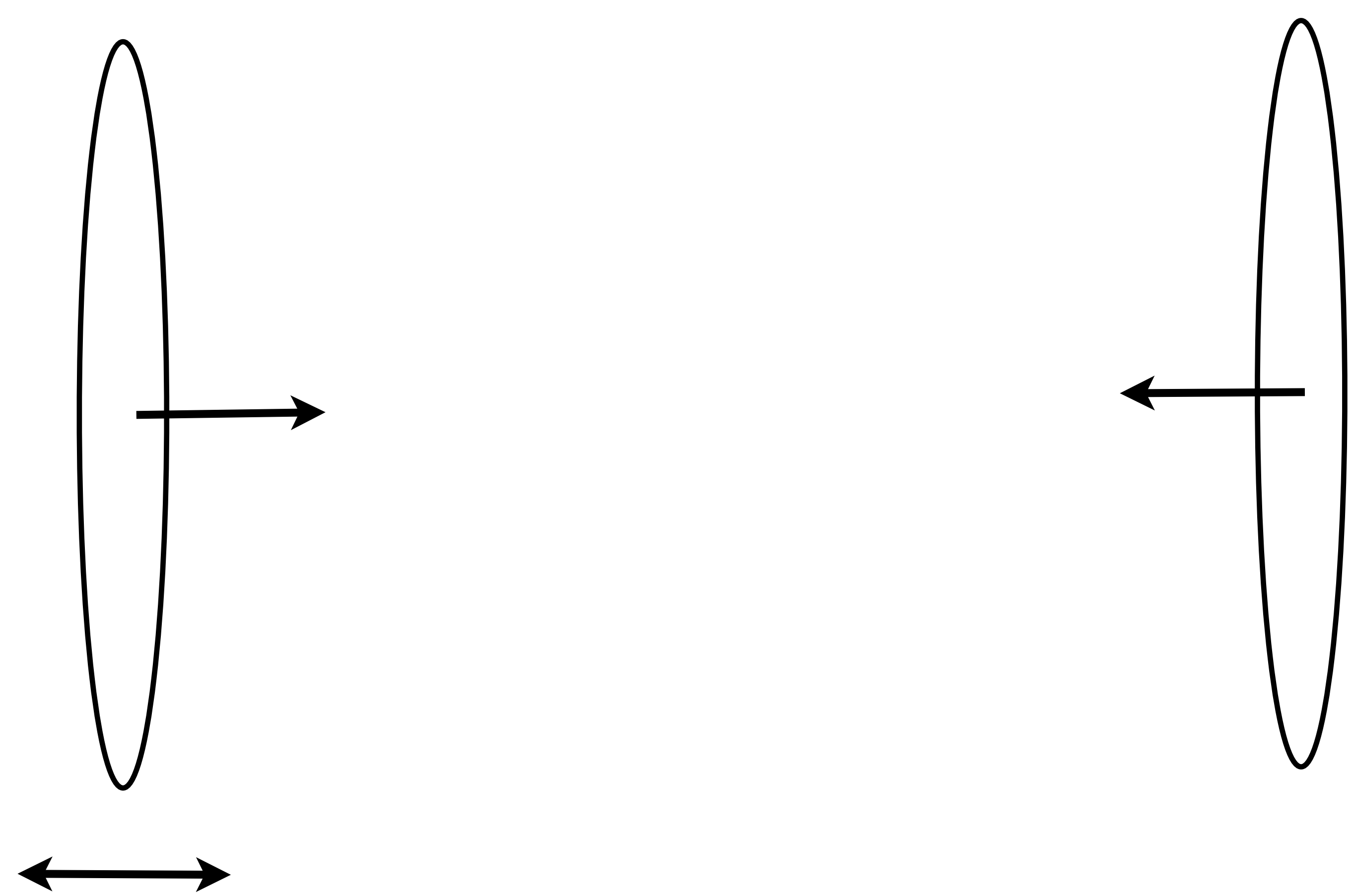
dN_{ch}/dy ~1000 (RHIC)
~1600 (LHC)

for 5% most central at midrapidity

(Alice, PRL 252302)

Stages of a heavy ion collision

1. Lorentz-contracted ‘pancakes’ hit each other



~10fm/100 (RHIC, @ $\sqrt{s_{NN}}$=200GeV)

1. A high density but out-of-equilibrium state is created; it expands longitudinally (τ~0-0.5÷1fm/c)

2. Rescattering becomes important: from here one assumes *local thermodynamic equilibrium*.

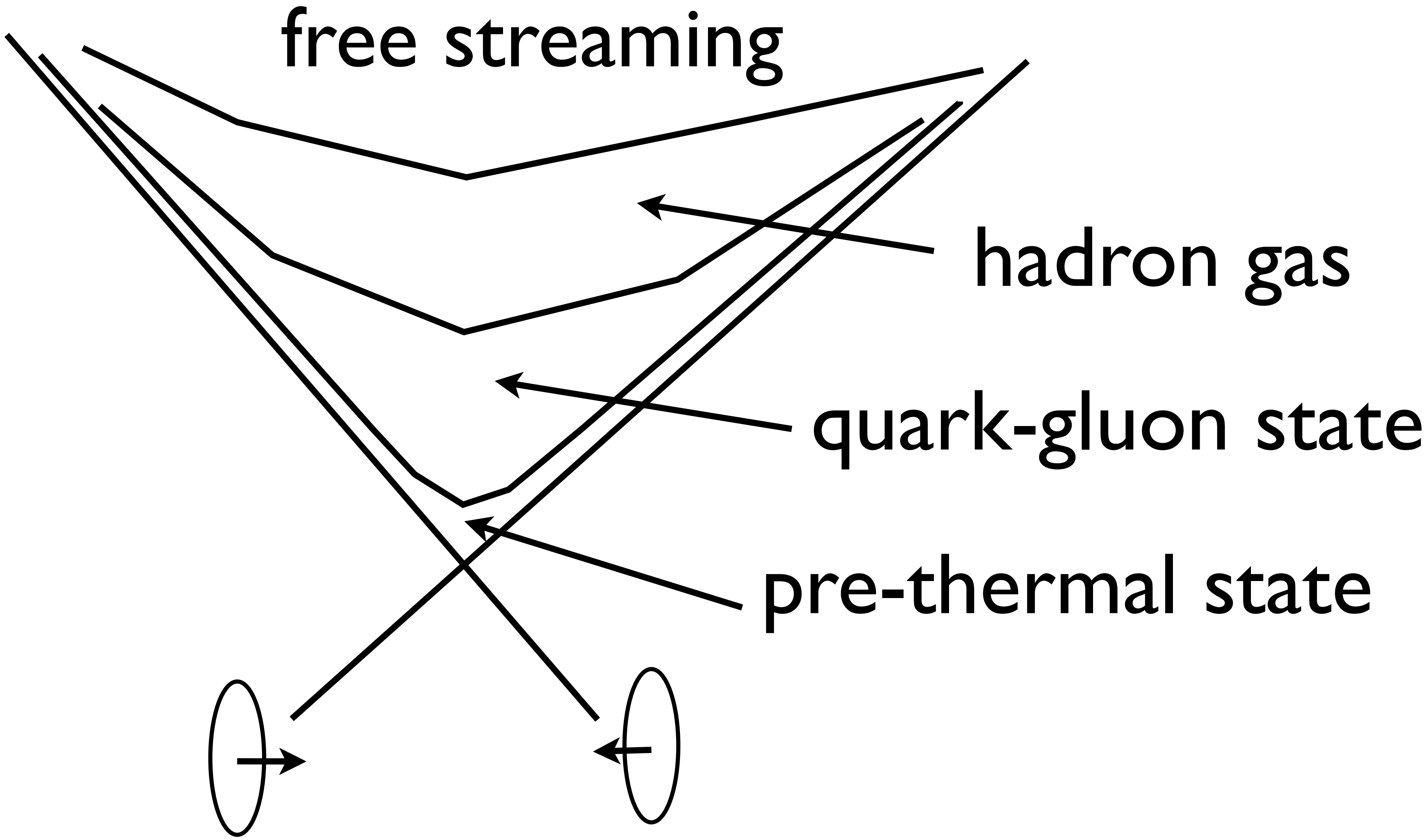
The system expands and cools hydrodynamically

3. T drops below T_c~170MeV (τ~10fm/c): *hadron gas*.

Around that time, *chemical freeze-out* occurs.

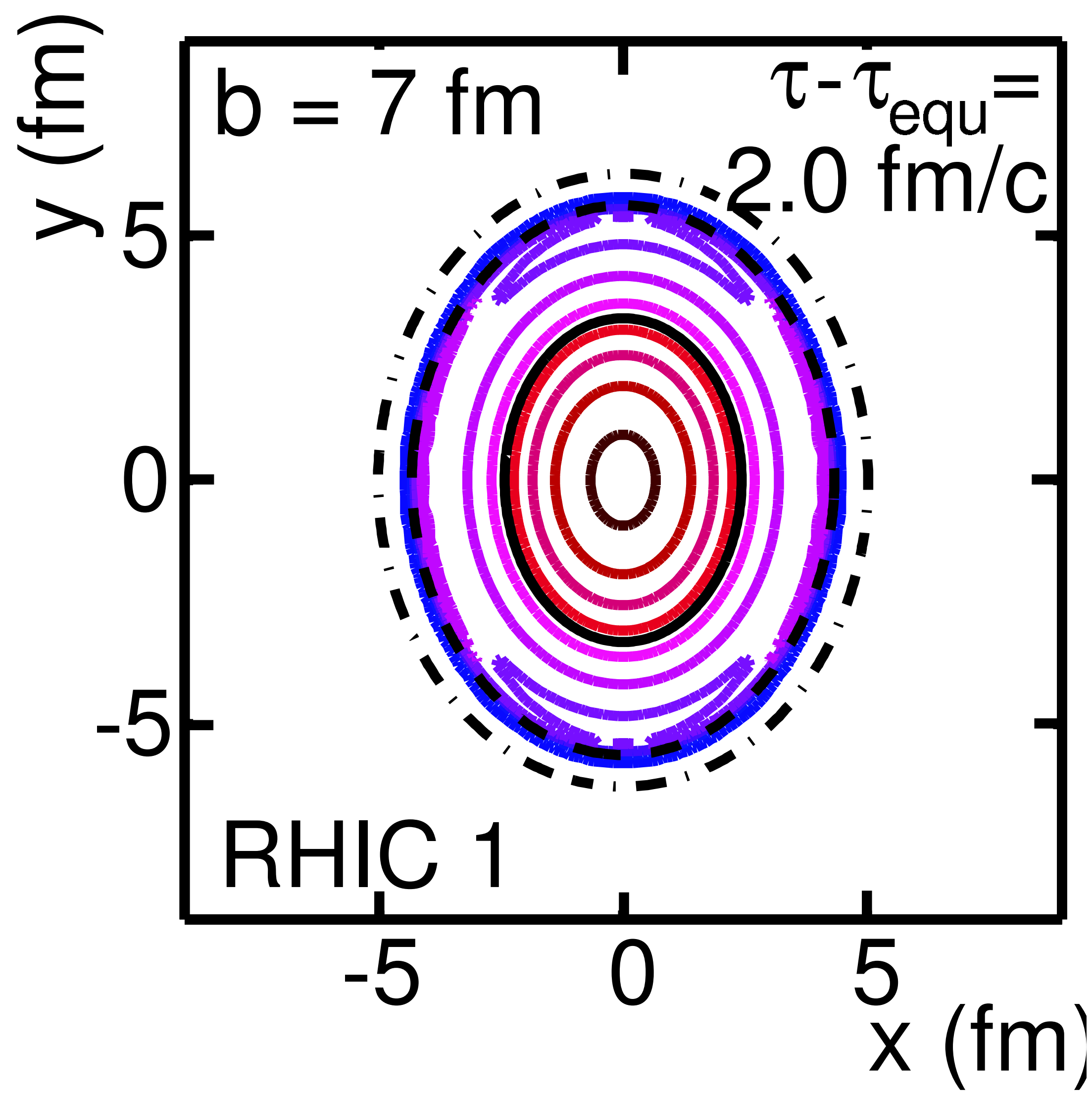
4. *Kinetic freeze-out* (τ~20fm/c): hadrons stream to the detector

Space-time diagram



Many stages/transitions seem prohibitively difficult to describe; fortunately, many of the details do not matter too much!

- What's the signature of rescattering?

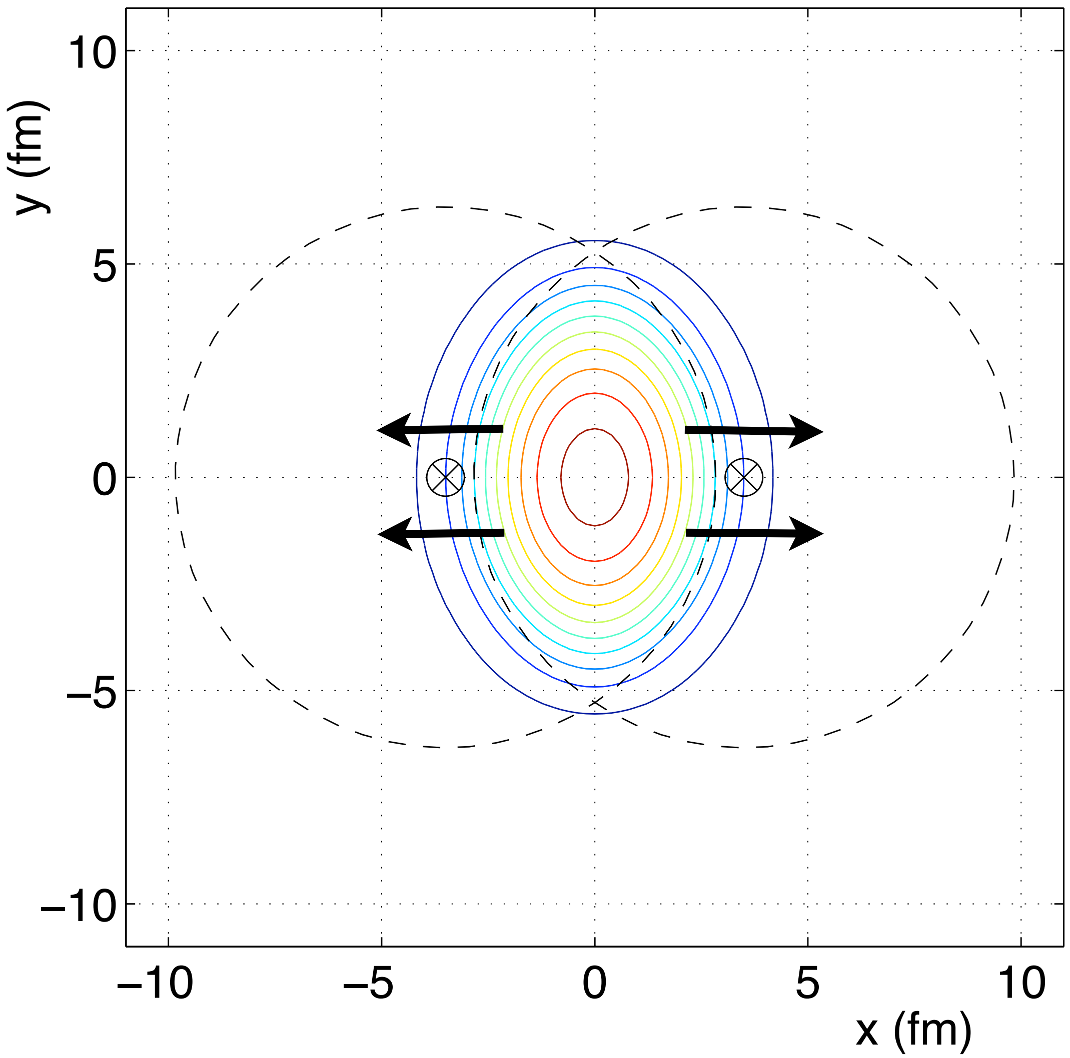


(picture from U. Heinz's excellent review, 0901.4355)

Rescattering converts density gradients into *acceleration*

('fluid-like' behavior)

- Radial acceleration per se is *not* observable
- However, initial conditions can be anisotropic



(again from U.Heinz's review)

- Beginning: *spacetime anisotropy*, mom. *isotropy*
- Final state: *momentum space* anisotropy

Hydrodynamics, I

- Hydrodynamics used to be the 'dynamics of water'
- In modern usage, it refers to the effective theory of [any] medium, on distances larger than a mean free path
- By definition, this describes *local thermodynamic equilibrium*
- There's a hydrodynamics theory for any fluid; it depends on its IR degrees of freedom and is parametrized by a set of [Wilson] coefficients.

Hydrodynamics, II

- Start from equilibrium. Say equilibra are parametrized by a temperature T and a 4-velocity, $u_\mu u^\mu = -1$.

$$T^{\mu\nu} = \eta^{\mu\nu} p(T) + u^\mu u^\nu (\epsilon(T) + p(T))$$

- 4 parameters; system closed by conservation laws. For nonrelativistic u:

$$\partial_t \vec{v} + \left(\vec{v} \cdot \vec{\partial}\right) \vec{v} \; = \; -\frac{1}{\rho} \vec{\partial} p \,, \qquad \text{[Euler's equations]}$$

$$\partial_t \rho + \rho \, \vec{\partial} \cdot \vec{v} + \vec{v} \cdot \vec{\partial} \rho \; = \; 0 \; .$$

[notice p acts like a potential: ∂p drives acceleration]

Hydrodynamics, III

- If T,u are not constant (but still slowly varying on mfp. scale), there will be small corrections.
- Most general first order correction: (in local rest frame)

$$T_{ij} = \delta_{ij} p - \eta \left[\partial_i u_j + \partial_j u_i - \frac{2}{3} \delta_{ij} \partial_k u_k \right] - \zeta \delta_{ij} \partial_k u_k \ \ (+\mathcal{O}(\partial^2))$$

- *shear* and *bulk* viscosities

Hydrodynamics, IV

- Linearized perturbations give *sound waves*, but also *diffusive modes*

$$(-i\omega + \frac{\eta}{\epsilon + p} k_z^2) u_x = 0$$

- These are acausal. This is not a conceptual problem, but *in practice*, causes numerical instabilities

Hydrodynamics, V

- The solution is to go to *second order*
- This removes the acausality and stabilize the dissipative effects
- Can be understand from Müller-Israel-Stewart theory

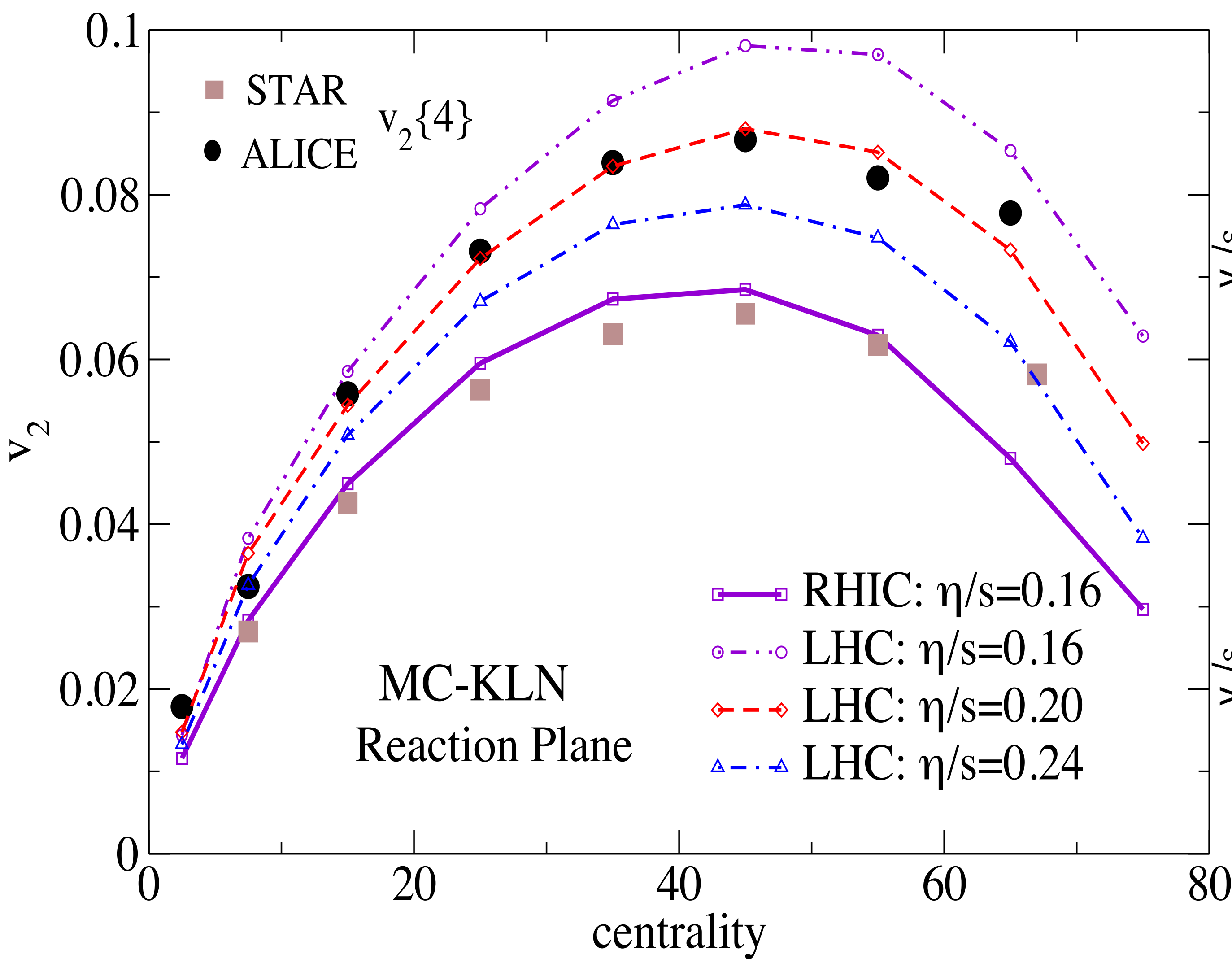
$$\pi_{ij} = -\eta[\partial_i u_j + \ldots] \to -\eta[\partial_i u_j + \ldots] - \tau_\pi u \cdot \partial \pi_{ij}$$

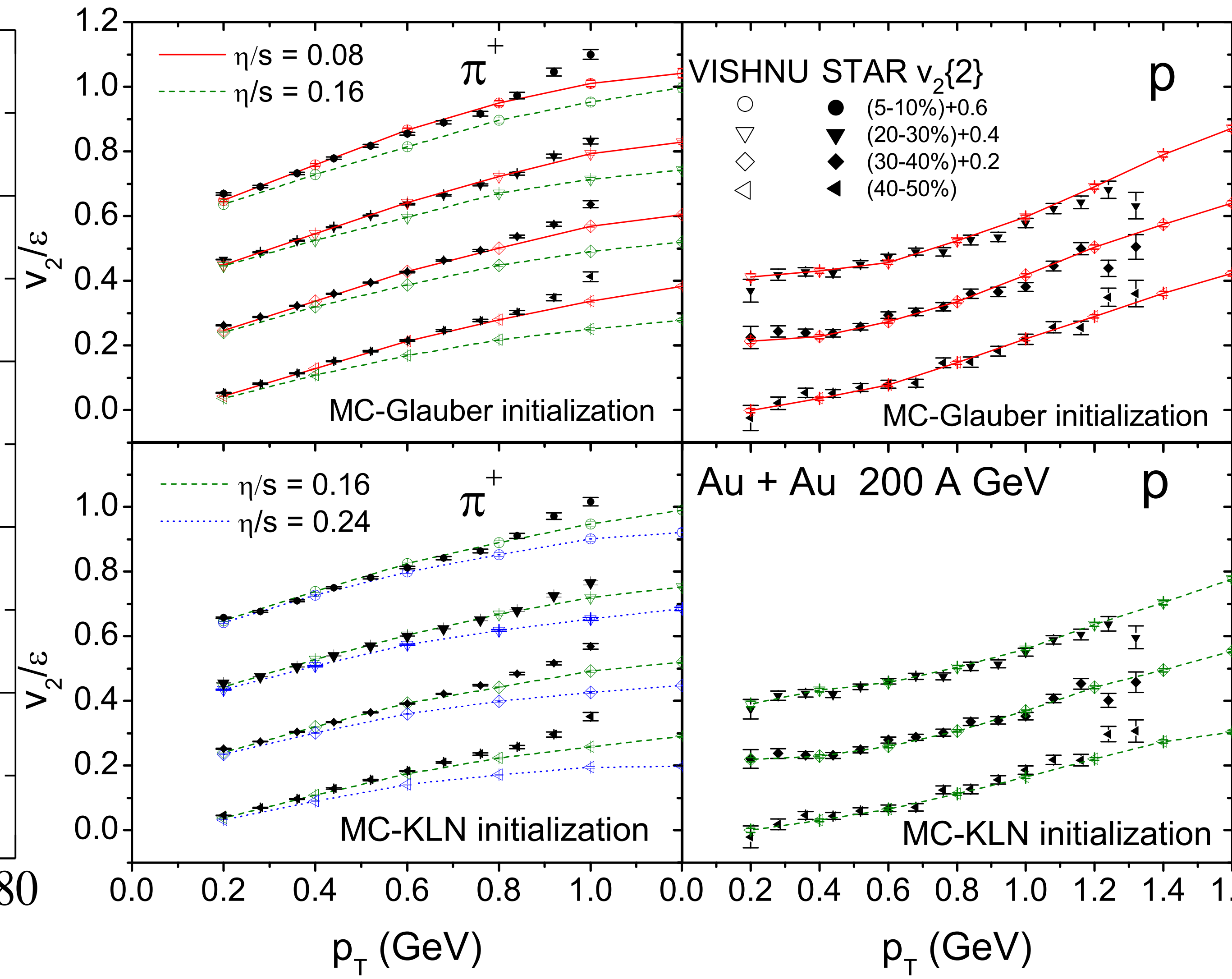
- The linearized shear mode becomes:

$$-i\omega + \frac{k_z^2}{1 - i\omega\tau_\pi} \frac{\eta}{\epsilon + p} = 0$$

Success of hydro

[plots from Heinz,Chen&Song 1108.5323]





$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1} 2 v_n(p_T) \cos(n(\phi - \phi_n))$$

present consensus:

$$4\pi \frac{\eta}{s} < 2.5$$

References

- There are many good textbooks on finite T field theory. I recommend:

  -Kapusta and Gale, *Finite temperature field theory: principles and applications*

  -M. LeBellac, *Thermal field theory*

  -A. Das, *Finite temperature field theory*

- I also found the following *lecture notes/reviews* helpful:

  -P. Romatschke, 0902.3663

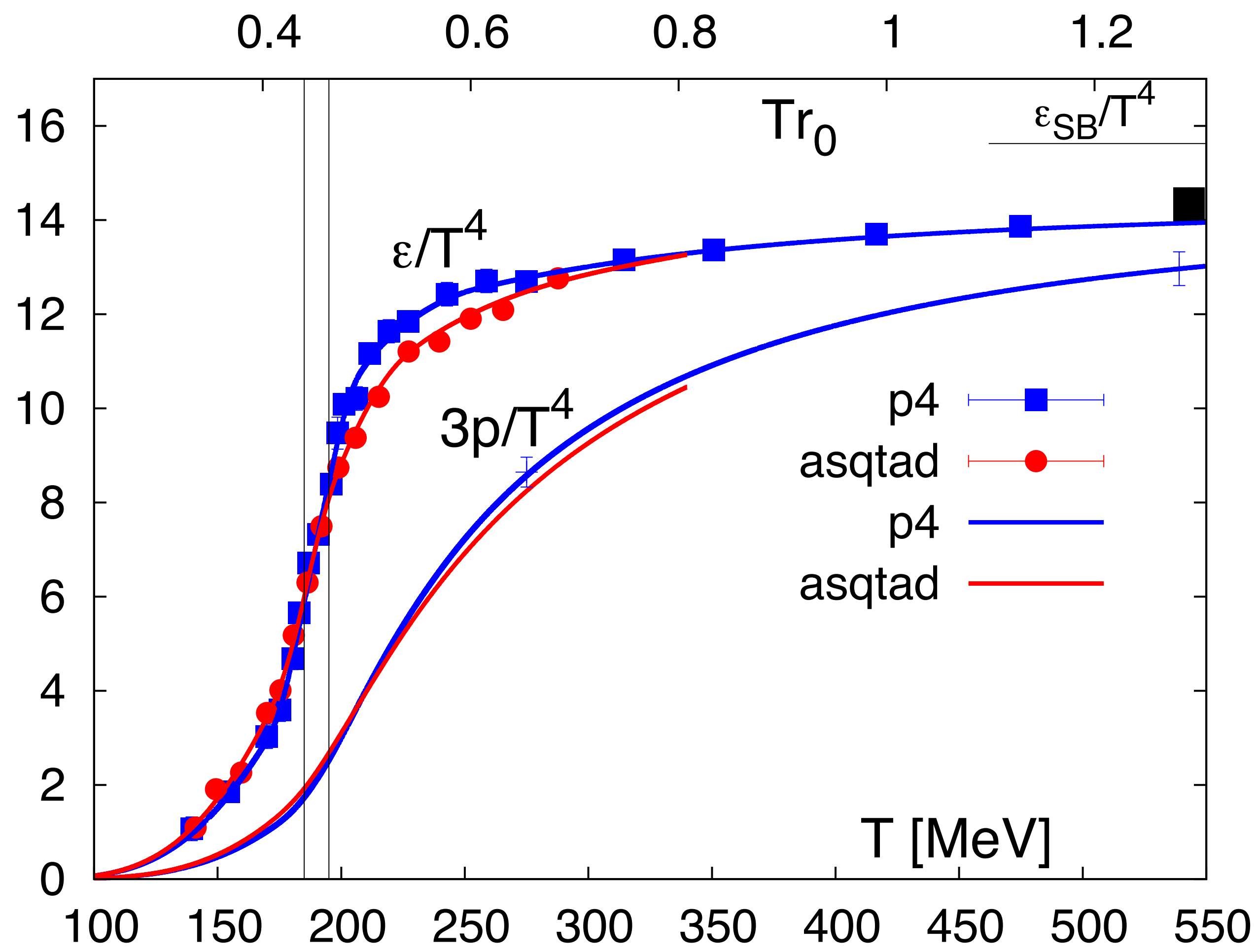
  -B. Müller et al., 1202.3233

  -E. Iancu, 1205.0579

  -U. Heinz, 0901.4355

[extra:]

- The QCD equation of state (2+1 flavors)



(Karsch *et al*, 0903.4379)